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SEISMIC VULNERABILITY OF GEOGRAPHICALLY DISTRIBUTED SYSTEMS

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SUMMARY

In the paper, an approach is proposed for the determination of the seismic vulnerability of geographically distributed systems, including cities and their associated interconnections and lifelines, based on a graph-structured representation of the information concerning the vulnerability of the system components and the expected earthquake intensity.

The system model is aimed to be part of a computerized logic procedure able to provide reasoning schemes over the expected scenarios. Reasoning is accomplished through a representation of the significant response parameters in terms of the theory of evidence. Response parameters are extended to include physical as well as social and economical aspects, whose degradation due to earthquake occurance can only be subjectively estimated.

The applicability of the procedure is discussed in view of the development of estensive seismic risk reduction policies, for situations typical of the mediterranean area.

INTRODUCTION

The study of seismic vulnerability aspects for buildings, and for several other kinds of single engineered systems is already developed to such an extent that widely accepted procedures are available to-date, and significant experience on their use is being accumulated in various countries.

However, the definition of a seismic risk reduction policy over an intensively populated area requires vulnerability information over single engineered systems to be integrated at different geographical scales. Integration implies consideration of other aspects, substantially different in their nature from earthquake loading resistance of physical devices.

The problem of seismic vulnerability of geographically distributed systems is mainly related to the definition of the three following concepts: the geographical extension, the system to be considered, resting over it, and the vulnerability of the system itself.

The geographical extension defines the scale of the study. Its characteristics may vary, depending on the conditions of the country under study.

Basically it is intended here that the geographical area under consideration will be characterized by substantial homogeneity in seismotectonic phenomena, social and economical development, construction technologies, infrastructures, etc.

The system is composed by the model of any entity, distributed over the area, the response of which to an hypothetical earthquake occurrence is to be forecasted.

The vulnerability of the system is a measure of the possible system response to an earthquake, expressed in terms of the expected degradation of parameters, representative of a global system status.

Making reference to situations typical of Central Italy, where earthquake prone areas to be studied may be defined, which include several medium size cities (10 to 15,000 inhabitants) together with their associated interconnections (roads, railways) and lifelines (water, electricity and gas supplies), the status of the system could be described by the total housing capacity, commercial or production activity, transitability, or availability of supplies.

For the study of the seismic response of lifelines several methodologies are known, based upon deterministic as well as on probabilistic formulations, leading to the determination of the expected damaging of pipelines, transportation and electrical networks.

Some of these methods, such as the ones proposed by Taleb-Agha (Ref. 1), Taleb-Agha and Whitman (Ref. 2), Mohammadi and Ang (Ref. 3), and by Moghtaderizadeh and Der Kiureghian (Ref. 4), provide valuable tools for the determination of the probability of failure of physical networks in seismic prone areas.

However, many of the above mentioned aspects cannot be treated in the same way either because probability measures are too strongly subjective or because mathematical modeling is too complex if not even impossible.

A different approach, based on a compatible representation of the system, is therefore developed in this paper with the aim of incorporating both heuristic and probabilistic formulations in a mathematical framework useful for the development of computerized logic procedures.

MODELING OF THE SYSTEM

The construction of computerized logic procedures, such as expert systems, requires knowledge formalization in order to simulate reasoning over facts. When facts derive from the behaviour of systems, knowledge representation shall address system structure and behavioural functions in addition to expert ability to deal with decisional problems of the specific domain. In the domain of utilization of large-scale vulnerability analyses for the planning of risk-reduction activities and resource allocation, the expert knowledge which can be formalized to-date is very limited, and the modeling of behaviour of vulnerable systems is restricted to the cases mentioned in the introduction.

Whithin this framework, modeling of the geographical structure of the system to be studied is perfomed in terms of a graph-theoretic equivalent, the elements of which represent vulnerable entities located within the area, and physical connections among them. Localized entities are associated to the nodes of the graph, and entities defineable as linear structures are associated to the branches. Physical entities are identified, based upon homogeneity in vulnerability characteristics. As a consequence, the branches always represent vulnerable entities, while the nodes may represent vulnerable entities as well as separations between branches of different vulnerability characteristics.

Let the N nodes $e_1 \ldots e_N$ and the M branches $E_1 \ldots E_M$ be the elements of the graph. Only those elements representing physical entities (all the branches and a part of the nodes) are characterized by a vulnerability index v_i or V_i, respectively. The seismicity of the area is considered in the model by the knowledge of the spatial distribution of expected earthquake intensity within a given reference time. From this knowledge an intensity index X_i can be defined for any element of the model. Vulnerability indices are constituted by sets of characteristic parameters for each element of the system, which can be correlated to an "efficiency" of the element.

In the generality of the cases, "efficiency" can be interpreted as a function of the expected damage which, in turn, is given in terms of damage probability matrices and associated uncertainties. Measuring the expected damage with a qualitative scale, the K degrees of which represent given intervals of a conventional damage index, each column of the damage probability matrix is the discrete probability distribution (probability mass function) of the damage degrees for a given seismic intensity. Uncertainties are accounted for by means of the theory of evidence (Ref. 5), leading to the definition of "plausibilities" and "supports" for any level of damage considered. According to previous research developments (Ref. 6), plausibilities and supports respectively represent the maximum and the minimum likelihoods that the expected damage will be measured by the corresponding degree of the scale. Such a formulation is considered to be the most general, allowing classical probability formulations (Bayesian), Boolean logic, and heuristic certainty factors to be interpreted in an unique mathematical framework.

In order to represent the response of the system in terms of evidential variables, the vulnerability analysis of each individual element of the model is interpreted as a knowledge source providing supports to propositions of the type:

"GIVEN THE EXPECTED SEISMIC EVENT OF INTENSITY X_i OVER THE i-TH ELEMENT, THE i-TH ELEMENT WILL UNDERGO A DEGRADATION WITH RESPECT TO PARAMETER P_l, MEASURED BY THE DEGREE g_k OF THE DAMAGE SCALE"

or, symbolically:

$$(P_l \in g_k | X_i)_i \qquad ; \qquad k = 1, \ldots K \tag{1}$$

To reduce the above statement to a computational form, it is assumed that a knowledge source is globally providing a unit support to the union of all the propositions related to the same parameter:

$$(P_l | X_i)_i = \bigcup_k (P_l \in g_k | X_i)_i \tag{2}$$

According to the theory of evidence, the total unit probability mass is however subdivided between an uncertainty $u[(P_l | X_i)_i]$, and a distribution of the supports $s[(P_l \in g_k | X_i)_i]$. For any of the degrees of the scale, the plausibility will be therefore given by:

$$p[(P_l \in g_k | X_i)_i] = s[(P_l \in g_k | X_i)_i] + u[(P_l | X_i)_i] \tag{3}$$

Actual determination of the probability mass distribution is depending on the nature of the parameters involved, and on the methods used for vulnerability analyses. Both objective and subjective probabilities could result from the analyses, and related to uncertainties could be determined from the absolute likelihood, and the relative applicability of the source.

ANALYSIS OF THE SYSTEM

For the global analysis of the system a methodology is proposed, which is based upon the following hypotheses:

I parameters characterizing the response of an individual element of the system are assumed to be statistically independent and not mutually exclusive;

II parameters characterizing the response of any element of the system are assumed to be statistically independent and not mutually exclusive with respect to the ones of any other element;

III the scales used to measure parameter degradation are assumed to be homogeneous or reconductable to the same scale by linear transformations;

IV the response of the global system can be evaluated by means of performance functions, functions of the parameters of the vulnerable elements which are encountered over paths across the graph representing the model of the system; degradation of the performance functions can still be measured by a scale consistent with the one used for the parameters of individual elements.

The analysis of the system can be therefore performed in two steps: in the first step all or the most relevant path of the graph can be detected; in the second step, the expected degradation of performance functions is evaluated by combining evidence over the parameters involved.

The methodological aspects of the approach, from the point of view of the application of the theory of evidence have been already discussed in a previous paper (Ref. 7). Major emphasis is given here to applicability considerations, and to the development of computerized logic procedures.

As a first comment, it should be noted that, when the method is applied to model the seismic response of lifeline type systems, and when the performance functions are expressed in terms of continuous random variables, all the procedures can be performed within probabilistic mathematical frameworks such as the classical approaches mentioned in the introduction.

In spite of the ability of evidential formulations to be reconducted to the same context, due to the possibility of giving the same mathematical formulation to subjective probability estimates and uncertainty modeling, the proposed methodology is substantially thought for being applied in a more qualitative context.

Such characteristics of the vulnerability analysis of geographically distributed systems arise when the methods of analysis are implemented to construct procedures able to reason over an expected loss of functionality of the system and to trace conclusions over the scenarios which may be encountered along different path within the modeled system. In this case, the use of rigorous mathematical formulations is unpractical, especially when it involves complex algorithms, and the use of heuristic rules to integrate evidence along the components of a path should be preferred.

Essentially, composition of evidence is intended to commit a probability mass (support) to any proposition asserting that a given performance function will be degradeted up to the k-th degree of the scale, i.e. to compute:

$$s[(\mathscr{P}\in g_k|X)_t] \qquad (3)$$

being t the generic path spanning the system. Of the total unit mass which is committeable to $\bigcup_k (\mathscr{P}\in g_k|X)_t$, a part will not in general be attributed to any of the propositions (3), forming the resultant uncertainty.

Several heuristic rules can be formulated to compute the distribution of supports and the uncertainty, depending on the nature of the performance functions. The simplest of these rules can be based over weighted averages of the supports contributed by the individual components of the path. Other rules can be derived from the application of the Dempster's rule of combination (Ref. 8), allowing algebraic-like operators to be defined to combine evidential variables representative of the contributions of the various components of the path.

Basically, the Dempster's rule combines two support distributions, and the related uncertainties, over different propositions of the type (1). The rule computes the resultant probability mass committeable to the intersections:

$$(P_1 \in g_m | X_i)_i \cap (P_h \in g_n | X_j)_j \quad ; \quad m, n = 1, \ldots K \tag{4}$$

The intersections are then summed up according to a heuristic interpretation of the resulting propositions.

The procedure has been partly implemented using a production system programming environment (Ref. 9) particularly suited for the inclusion of algorithmic routines. In particular, the implementation actually includes step 1 of the analysis and some routines for the combination of evidential variables over the paths. The computer program has been realized as a part of a more general expert system, which will be developed as soon as domain specific knowledge will be available in appropriate formalization.

CONCLUDING REMARKS

The application of the above described methodology has been studied over the test case depicted in Fig. 1. The system which has been modeled consists of a part of the Umbria region, in Central Italy, including some medium to small inhabited nuclei, and road segments of various importance interconnecting the nuclei. The study has been performed in the framework of a research program sponsored by the Umbria Regional Administration concerning seismic vulnerability, and was aimed to develop procedures useful in the definition of a global seismic risk reduction policy.

The description of the response of the system has been given in terms of the following parameters:

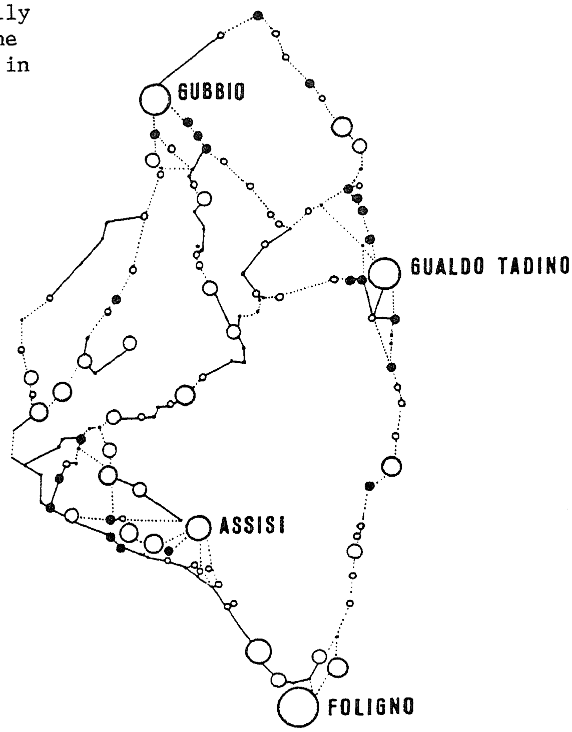
a) for inhabited nuclei: usability of the buildings, as a function of the expected physical damage;
b) for road segments: transitability, as a function of the expected instability of the adjacent slopes.

Physical damaging of the buildings was inferred from the results of an extensive vulnerability survey performed in the town of Gubbio (Ref. 19). Transitability of roads was instead based on subjective evaluations.

As a part of the study, the construction of heuristic rules for composition of evidential variables has been tested, with reference to performance functions qualitatively expressing the loss of functionality due to expected damaging only of individual elements. A variety of alternatives has been taken into account, ranging from weighted average performed globally on the path components, to "best" or "worst" estimates obtained with repeated applications of the Dempster's rule.

The study has indicated that the methodology is substantially able to give very synthetic information about the system response. Tuning of the rules, especially concerning the role of uncertainties, should however be carefully examined over more extensive testing.

Fig. 1 - Example of geographically distributed system: some urban nuclei and roads in Central Italy (Umbria)



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